

LCA Case Studies

Life Cycle Assessment as a Tool for Improving Process Performance: A Case Study on Boron Products

Adisa Azapagic¹, Roland Clift²

¹Department of Chemical and Process Engineering, University of Surrey, Guildford, Surrey, GU2 5XH, UK

²Centre for Environmental Strategy, University of Surrey, Guildford, Surrey, GU2 5XH, UK

Corresponding author: Dr. Adisa Azapagic; e-mail: A.Azapagic@surrey.ac.uk

Abstract

This paper explores the use of LCA as a tool for process environmental management, thereby moving the focus from product to process oriented analysis. The emphasis is on Improvement Assessment in which the "hot spots" in the system are targeted for maximum environmental improvements. In this context, it is useful to use multiobjective optimisation which renders Valuation unnecessary.

The approach is illustrated by the case study of the system processing boron ores to make five different products. The results of Inventory Analysis and Impact Assessment are presented and discussed. In Improvement Assessment, a number of improvement options are identified and evaluated, using system optimisation. It is shown that the site environmental performance can be improved over current operation by an average of 20% over the whole life cycle. Thus the study demonstrates that the optimisation approach to environmental process management may assist in identifying optimal ways to operate a process or plant from "cradle to grave". This may help the process industries not only to comply with legislation but also provide a framework for taking a more proactive approach to environmental management leading to more sustainable industrial operations and practices.

Keywords: Boron products; environmental impacts; environmental system management; Life Cycle Assessment; system optimisation

Introduction

Traditionally, Life Cycle Assessment has been product-focused and has rarely been applied to analysing and improving the performance of a process facility. The study presented here shows how LCA can be used for site environmental management; in particular, for reconciling often difficult requirements to achieve improved environmental performance by modifying the operation of existing plant. Even for the purpose of process management, it proves useful to follow the standard LCA methodology (CONSOLI et al., 1993), through the phases of Goal Definition and Scop-

ing, Inventory Analysis and Impact and Improvement Assessment. In this kind of application, Improvement Assessment amounts to assessing possible changes in the operation of the process and identifying operations within it which could be upgraded to improve the performance over the whole life cycle. For this purpose, as discussed later, Valuation proves to be unnecessary.

The system selected for study produces five different borate products and therefore represents a multiple-function system in which the burdens and impacts have to be allocated among the co-products. Since allocation is relevant for product-oriented LCAs only, this aspect of the analysis is not discussed here but can be found elsewhere (AZAPAGIC, 1996; AZAPAGIC and CLIFT, 1998, 1999a, 1999c).

Although the emphasis in this paper is on the use of Improvement Assessment for plant management, other phases of the boron LCA are also included for completeness. These results are presented next.

1 Goal Definition and Scoping

1.1 Purpose

The study summarised here was carried out primarily for internal use by the company operating the boron mine and mineral processing plant, in order to identify the key unit processes in the life cycle and hence opportunities for improving the environmental performance of the whole system.

1.2 Scope

The system under study is shown schematically in Figure 1. Further details can be found in AZAPAGIC (1996). The system includes all activities from extraction of raw materials from the earth up to packing of the following five boron products: 10 Mol borate ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$), 5 Mol borate

($\text{Na}_2\text{B}_4\text{O}_7 \cdot 4.67\text{H}_2\text{O}$), boric acid (H_3BO_3), anhydrous borax ($\text{Na}_2\text{B}_4\text{O}_7$), and anhydrous boric acid (B_2O_3). Because of the vast number of possible uses of the products, use and disposal are not considered, making this essentially a "cradle-to-gate" study. However, the study provides results which could be used by customers of the boron products. In that case, allocation of the burdens among the co-products is necessary. Since the product outputs can, within limits, be changed independently, the "marginal approach" based on physical causality can be used to allocate the burdens in this system (see AZAPAGIC 1996; AZAPAGIC and CLIFT, 1998, 1999a, 1999c).

As in many LCA studies, it is useful to divide the product system into Foreground and Background subsystems. "The set of processes whose selection or mode of operation is affected directly by decisions based on the study" defines the Foreground (CLIFT et al., 1998). The Background comprises all other processes which supply material or energy to the Foreground, especially where the supply takes place via a homogenous market. Processes in the Foreground should be described by primary data, but secondary or generic data can be used to describe the Background (UDO DE HAES et al., 1994; CLIFT et al., 1998). The functional unit is defined by reference to the Foreground.

Figure 1 shows the distinction between Foreground and Background for this case study. The Foreground is represented by the central process, i.e. production of the five boron products. It includes all activities from extraction of boron up to the packing and preparing for shipping of the boron products. On-site cogeneration of energy as well as transport in the mine are also in the Foreground. Data for the Foreground system are based on the actual operation of this system during one year and are thus the primary data. The Background comprises the life cycles of product systems shown in Fig. 1 which supply the materials to the Foreground. Their flow diagrams are shown in the Appendix. The data for the Background activities in this work are taken from the commercial databases PEMS (Pira International, 1994) and SimaPro2 (PRé Consultants, 1995) and are therefore considered to be generic, representing the average mix of technologies. The assumed fuel mix for electricity generation in the Background system is represented by an average fuel mix in the US¹.

Excluded from the system boundaries are:

- use and disposal of the boron products
- manufacture of minor ancillary materials, such as chemicals for water treatment (NaCl , NaOH and HCl), sodium dithionite ($\text{Na}_2\text{S}_2\text{O}_4$), hydrogen peroxide (H_2O_2), and flocculants
- manufacture and maintenance of capital equipment (except for the maintenance of the trucks in the mine)

¹ Coal (24%), fuel oil (41%), natural gas (24%), hydropower (3.5%) and nuclear power (7.5%) (WRI, 1991).

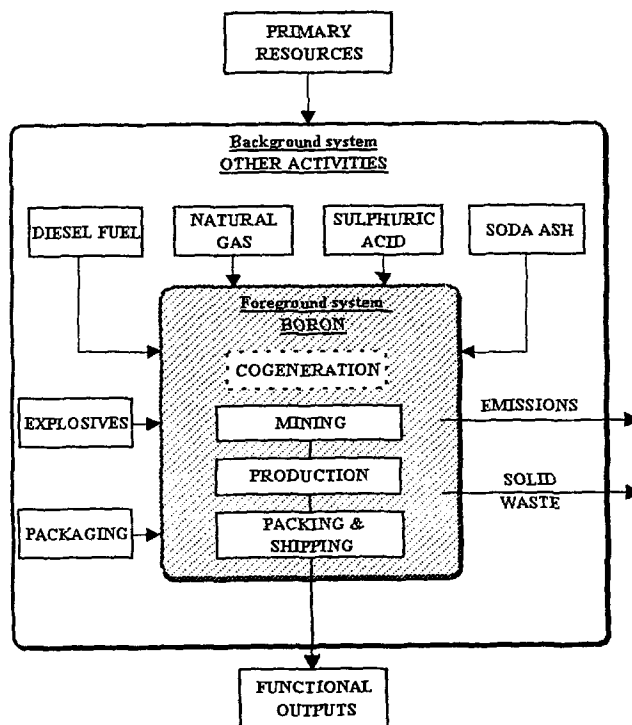


Fig. 1: Schematic representation of the Background and Foreground subsystems

- manufacture, operation and maintenance of heating and lighting equipment.

1.3 Functional unit

The functional unit has been defined under the assumption that the study will be used for internal purposes, in which case the engineers and operators are concerned with assessing and improving the process performance on the basis of its actual operation. Hence, the functional unit has been defined as "operation of the system for one year". The product outputs for this functional unit are shown in Table 1. To preserve commercial confidentiality, the figures given are not based on actual production or sales but represent a possible scenario for this system and therefore provide a hypothetical but feasible basis for discussion in this paper.

Table 1: Functional unit and related output of the boron products

| Functional unit Product \Downarrow | Operation of the system for one year (t/yr) |
|---|--|
| 10 mol | 81000 |
| 5 mol | 810000 |
| BA | 150000 |
| AB | 16000 |
| ABA | 5000 |
| TOTAL | 1062000 |

1.4 Data sources and quality

The primary data for the Foreground processes were obtained directly from the company. The data are representative of operation which has not changed significantly in the preceding years. Production data, including data on mass and energy flows, are derived directly from process measurements, while the environmental data represent the best estimates obtained using the methodology recommended by the US Environmental Protection Agency (1995).

The generic data for the Background describe the life cycles of fuels (natural gas and diesel fuel) and materials (sulphuric acid, soda ash, explosives and packaging) used in the Foreground. As mentioned previously, these data were taken from commercial databases and where possible were cross-checked.

2 Inventory Analysis

2.1 Analysis of product system

The Foreground operations are shown in more detail in Figure 2. They consist of two main parts: the mine and the plant. The plant includes Production, Packing and shipping², and Steam plant and Cogeneration. The broken lines in Fig. 2 represent the boundaries between these subsystems.

Two boron minerals with different borate content, borax ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$) and kernite ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 4\text{H}_2\text{O}$), are extracted in the mine, crushed and transported to the adjacent plant. 5 Mol and 10 Mol borates are produced by dissolving borax and kernite in water. Na-borates are then separated from insolubles, crystallised and dried to produce powder products. Boric acid (BA) is produced in a separate plant, by reacting kernite ore with sulphuric acid. The rest of the process is similar to the 5 Mol and 10 Mol production. Anhydrous borax (AB) and anhydrous boric acid (ABA) are made in high-temperature furnaces from 5 Mol borate and BA, respectively. All products are then either packed or shipped in bulk. Electric energy and the steam for the system are provided by the on-site natural gas cogeneration facility, which meets most of the electricity and steam demand. The additional steam is provided by the steam plant which is also fired by natural gas. The overburden from the mine and the gangue from the process are stocked in piles in the mine. The waste water from the refinery is discharged into the on-site self-contained ponds.

2.2 Allocation of environmental burdens

As mentioned previously, allocation of the burdens between the co-products in the Foreground system is not relevant for the purpose of this study. However, the only other part

² Shipping includes loading the packed products into trucks or bulk products into containers but not their transportation to customers.

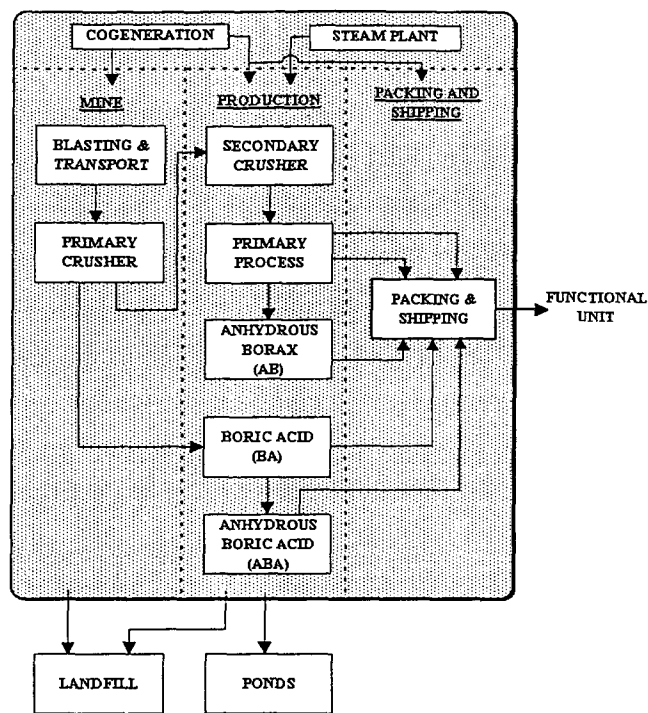


Fig. 2: Flow diagram of the Foreground system

of the Foreground where allocation is necessary is the Cogeneration facility. The allocation problem in this plant arises because some of the electricity is exported from the system while all cogenerated steam is used at the site. For that, the "avoided burdens" allocation approach has been used, whereby the burdens from electricity produced by natural gas, the only realistic alternative to cogeneration, have been subtracted from the burdens arising from the cogeneration facility. For a more detailed account, see AZAPAGIC (1996) and AZAPAGIC and CLIFT (1999c).

The data for the Background system are taken from databases describing average technology mixes, usually without clear specification of the basis for allocation but probably derived from some arbitrary basis such as mass. This is a general problem which is present in commonly used databases which often causes discrepancies between the analysis of the Foreground and Background (CLIFT et al., 1998).

2.3 Environmental burdens

Two sets of results are shown here. One compares the Foreground and Background systems in terms of their relative contributions to the total environmental burdens (\rightarrow Fig. 3), while another shows the contributions to the burdens of individual operations (\rightarrow Fig. 4).

The results shown in Figure 3 reveal that the Background system is mainly responsible for resource depletion, except for gas reserves, other non-renewables (boron mineral) and wa-

ter, which are primarily used in the Foreground system. The Foreground also contributes 35% to the oil consumption. Furthermore, it shows a major contribution to the emissions of CO₂ (75%) and metals to air (99.9%) and water (83%); waste water (72%); TDS and TSS (99.8%); and landfill weight (98%) and volume (95%). The Background is responsible for the other emissions to air and water.

The same results are shown in a different way in Figure 4 to identify contributions to the burdens of individual operations within the Foreground system. Although not shown explicitly, the Background system is included within the corresponding operations in the Foreground. The figure reveals that Primary process (productions of 5 and 10 Mol borates) and Total steam production (steam cogenerated in the Cogeneration plant plus steam from the Steam Plant) are, in total, responsible for 80% of nuclear and hydro-electricity. This energy is consumed in the Background system in the life cycle of natu-

ral gas (→ Fig. A.1). Primary process and Steam production operations are also mainly responsible for the consumption of gas and water, most of which are used directly in these two processes – gas for electricity generation and water for steam and as a solvent for the boron mineral. The BA plant consumes around 60% of the coal reserves in the system, almost all of which is used in the Background system in the life cycle of sulphuric acid (→ Fig. A.5). Packing and shipping are the main users of renewable resources used for paper bags (→ Fig. A.6), while oil reserves and other non-renewables (i.e. borax and kernite ores) are mainly used in the Mining operations. Some oil reserves (25%) are also used in BA plant, but are again part of the sulphuric acid life cycle. All other operations contribute significantly less to the total resource consumption.

The Mining activities are the main source of emissions of metals (95%) and dust (42%) to air as a direct consequence

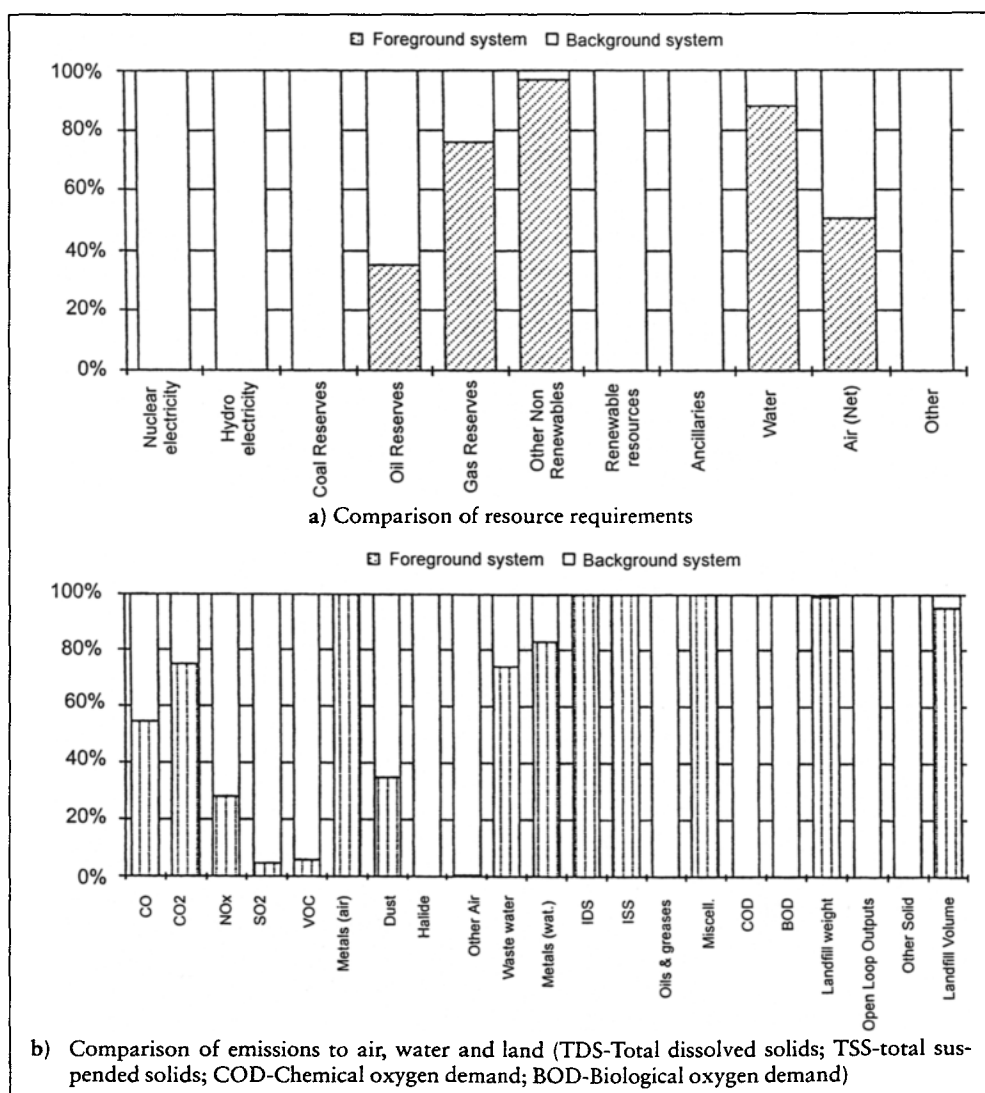


Fig. 3: Contributions of the Foreground and Background systems to environmental burdens

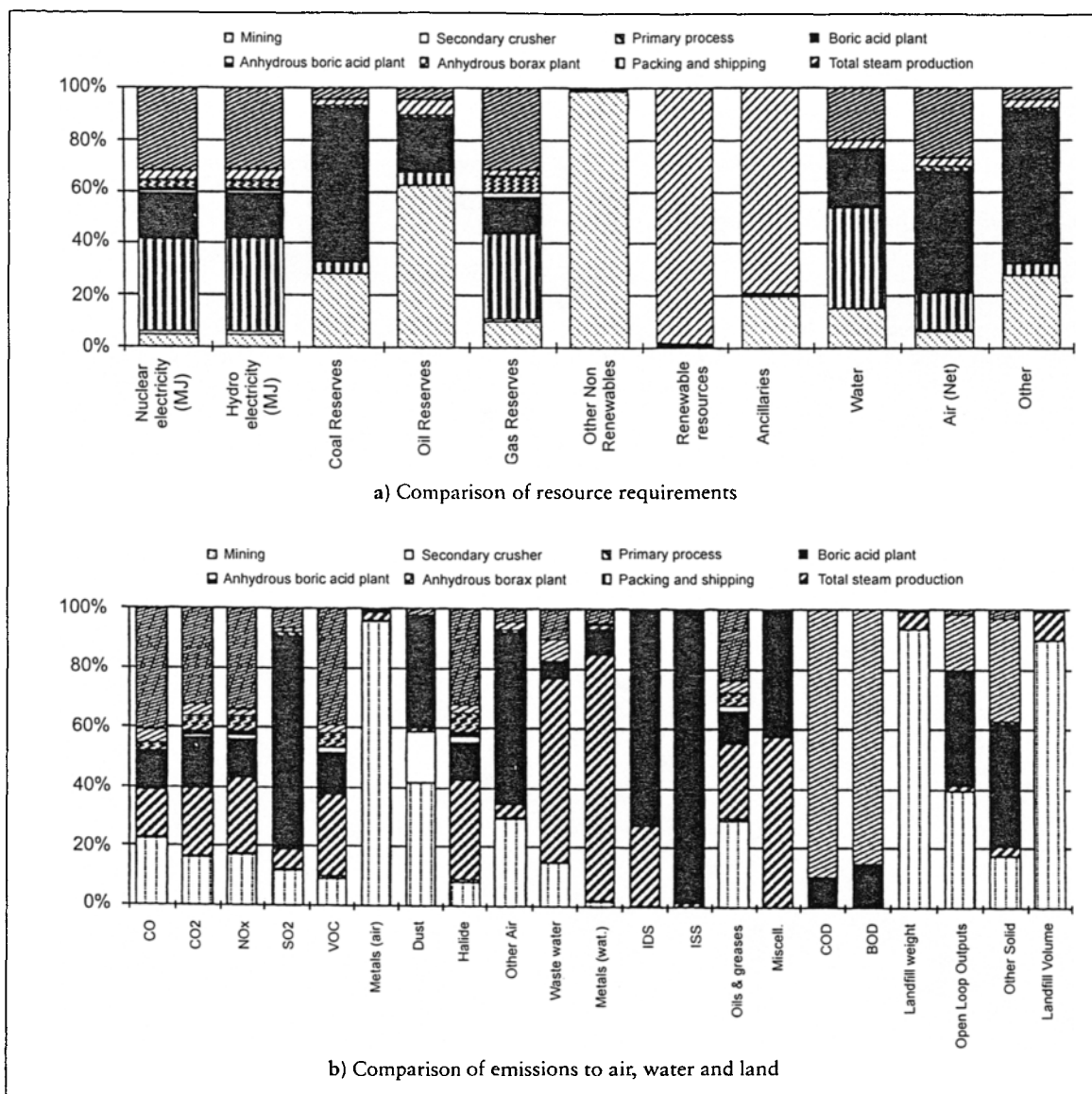


Fig. 4: Environmental burdens from operations in the boron system

of mining. This part of the system also contributes to 90% of Landfill volume and weight. The SO₂ emissions, TSS and TDS result from BA production. While the emissions of SO₂ stem from the life cycle of sulphuric acid in the Background system, TSS and TDS are generated directly in the BA plant. Most of the emissions of CO, CO₂, NO_x and VOC are generated by the Total steam production (Cogeneration facility), while the halides, waste water and metals to water are emitted directly from the Primary process. The COD and BOD are attributed to the paper bag production in the Background system, because of the high water consumption in this process.

3 Impact Assessment

The Problem oriented approach (HEIJUNGS et al., 1992) has been used to calculate the impacts from the Boron system. These results are shown graphically in Figures 5 and 6. The Foreground system contributes most of the Abiotic resource depletion, mainly related to the extraction of boron reserves in the mine (→ Fig. 5). Greenhouse effect (direct) is also a consequence of the activities in the Foreground, more specifically, energy use in the Primary process and Steam production. Ozone depletion, Acidification and Nutrification are also mainly contributed by the Primary process and Steam production; however they originate in the Background from the life cycle of natural gas. Thirty five percent of Acidification

also results from operation of the BA plant, which is again due to the sulphuric acid in the Background. Photochemical smog is generated mainly by Steam production (70%) and a small proportion is related to the Primary process and BA production. However, all of that is due to electricity generation and the life cycle of natural gas in the Background.

The Primary process is the major source of Aquatic toxicity, with a minute contribution from BA production. However, Aquatic toxicity is considered to be only a potential impact here, because 99.9% of it represents arsenic in the waste water, which is discharged into self-contained ponds. The ponds are either lined and covered or are scheduled for reclamation. In either case, the waste water does not leave the system and the risk of leaching into the ground water is minimal. The Landfill volume is mostly generated in the Mine as 90% of this impact is related to overburden. The remaining 9% is gangue from the Primary process and from BA production, while approximately 1% comes from the other life cycles in the system.

The LCA results presented in this and the preceding section provide valuable information on the contribution of individual processes to the total environmental burdens and impacts from the boron system. On this basis, the possibilities for improving the environmental performance of the process can be identified and evaluated. This is a part of Improvement Assessment which is discussed in the following section.

4 Improvement Assessment

As stated in Section 1, the purpose of this LCA study was to identify and evaluate possibilities for improving the environmental performance of the boron process from cradle to gate. Hence, the first step is to identify the "hot spots" in the system, i.e. the subsystems that contribute most to the total burdens and impacts. The efforts to improve performance are then aimed at these subsystems to achieve the maximum decrease in total environmental impacts.

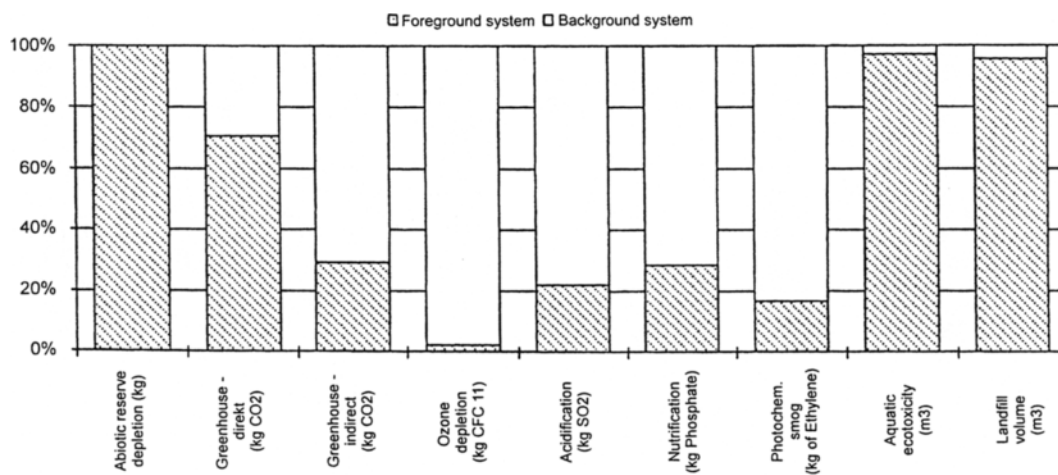


Fig.5: Contributions of the Foreground and Background systems to environmental impacts

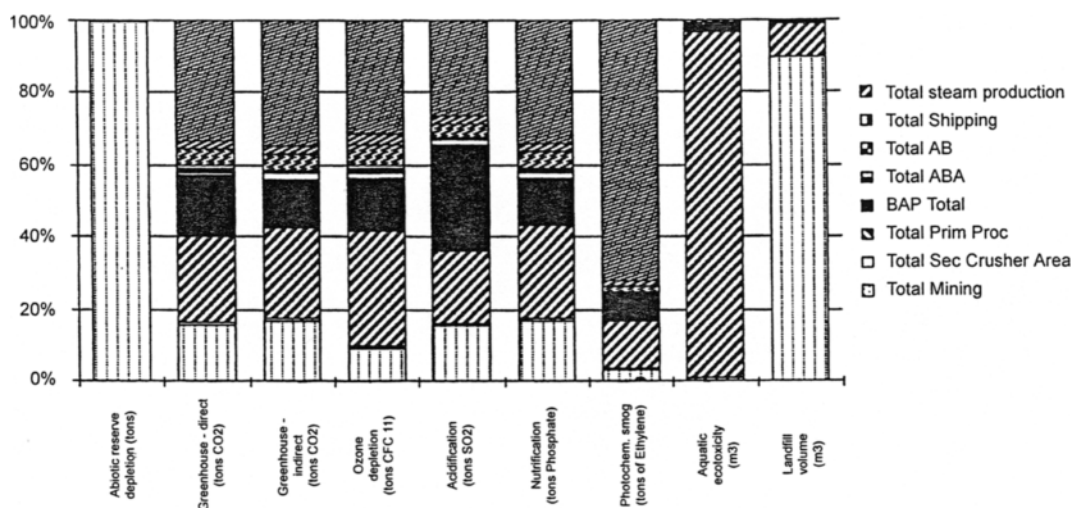


Fig. 6: Environmental impacts of operations in the boron system

(Greenhouse - Indirect: a potential of CO₂, NO_x and hydrocarbons to cause tropospheric ozone formation which then acts as a greenhouse gas)

The results of the Inventory and Impact Assessment phases (see Figs. 4 and 6) indicate the subsystems that contribute to most of the burdens and impacts. They include Mining, Primary process, Steam production, Boric acid plant, and Packing and shipping. Therefore, these subsystems are the first to be considered for targeted system improvements. Other subsystems, such as the Anhydrous borax plant and Anhydrous boric acid plant, could also be included in the improvement analysis; however, improving their performance at this stage would not reduce the impacts significantly, so that for the purposes of the analysis presented here these subsystems are not considered further.

Once the "hot spots" have been identified, the next step is to identify feasible options for improvements. This could include changes as small as improving the efficiency of existing unit operations, up to step changes in input materials, technologies or suppliers. To illustrate the use of LCA as a tool for improving process performance, several alternatives to the way the system is operated at present are considered. In the Mining subsystem, a significant part of the burdens and impacts is attributed to ore transport within the mine. Therefore, one of the possibilities to reduce the burdens from this subsystem is to consider conveyors as an alternative transportation means. Further, the burdens from the Primary process are mainly attributed to the product dryers; since three different dryers are in use, one of the improvement possibilities is to identify the best dryers and their optimal combination in use. A further option would be to install low- NO_x burners in the dryers to reduce NO_x emissions and the related impacts. Another possibility for reducing the impacts from this subsystem is to identify the optimum ratio of kernite to borax ore, subject to the process constraints. Moreover, in the Steam production subsystem, steam can be generated in both Steam and Cogeneration plants so that identification of the optimum use of these plants could bring further improvements in the system. Finally, since most of the burdens from

Packing and shipping arise from the life cycle of packaging, the type of packaging that causes the least environmental burdens could also be identified.

The final step in Improvement Assessment is evaluation of the improvement possibilities and identification of Best Practicable Environmental Option (BPEO). The improvement options can be evaluated either analytically or by using mathematical modelling. For simpler systems, it may be intuitively obvious which options would be the best; however for problems that are not as straightforward, more elaborate techniques may be needed. The authors have developed a system optimisation approach to facilitate the identification and choice of BPEO in Improvement Assessment. This approach, which is described in detail elsewhere (AZAPAGIC, 1996; AZAPAGIC and CLIFT, 1998, 1999b), has been applied to this case study to evaluate the above options and possible improvements in the system.

The boron optimisation model is described by the material balances and energy flows in the system from "cradle to gate" following the results of the Inventory phase. The system is optimised on the objective functions defined by environmental burdens and impacts. The results of optimisations, in which each burden and impact was optimised in turn, are shown in Figures 7 and 8.

Figure 7 indicates that the existing operations of the boron system can, on average, be improved by 11.5%, with the highest improvement in Oil reserves of 43.5%. The environmental impacts follow similar trends: the average reduction in the optimised system is 20%, while Photochemical smog can be decreased by 62%. On closer inspection of the optimisation results, the reasons for these significant improvements become apparent. The ratio of kernite to borax ore is increased from the current value of 0.2 to the optimum value of 0.4. Since this increases B_2O_3 content in

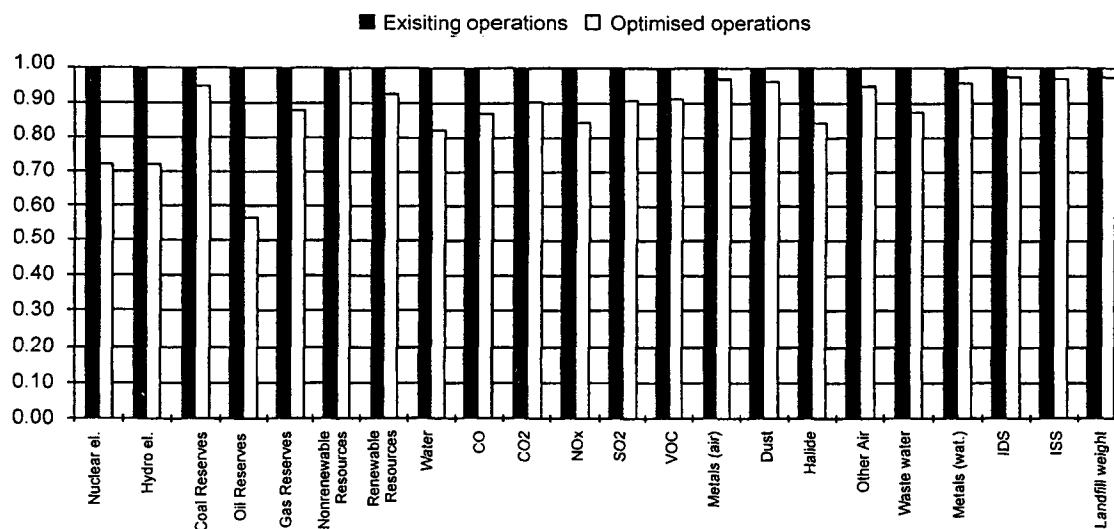


Fig. 7: Improvements in the boron system: environmental burdens

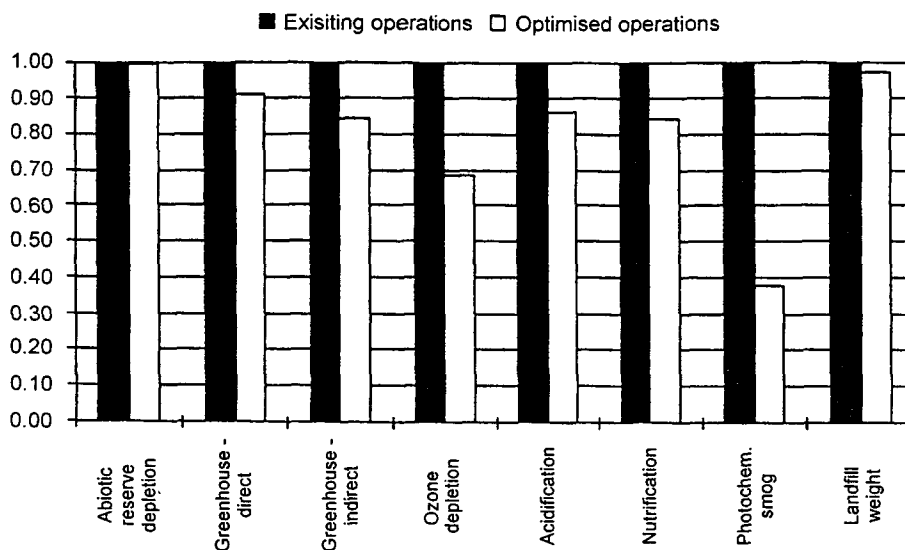


Fig. 8: Improvements in the boron system: environmental impacts

the process, the total amount of ore required is thus reduced. This has a direct effect on reducing the extent of the mining operations and the related environmental burdens from the mine. Moreover, the increased kernite to borax ratio also causes a decrease of the insolubles to borates ratio in the dissolvers and thickeners. This, in turn, results in reduced gangue, energy requirements, and other related environmental burdens from the Primary process.

Reductions of the environmental burdens from the Primary process are also achieved by producing 5 Mol in the Rotary dryer, instead of the Fluid bed dryer as in the current operations. The reduction in the burdens and impacts from the dryers due to this change amounts to 60% per unit of 5 Mol produced. A further reduction of up to 85% per unit of product in NO_x emissions (and the corresponding impacts) can also be achieved by installing low- NO_x burners in the dryers.

A decrease in the burdens and impacts in the optimised operations is also possible by using different transportation means in the mine. However, unlike the other improvement options discussed so far, it is more difficult to decide which type of transport is a better choice. If, for example, the aim is to minimise gas consumption, transport by trucks is a more environmentally acceptable solution, because the electricity used to drive the conveyors is generated from gas. Optimisation on fuel consumption, on the other hand, favours the use of conveyors because of the reduced need for diesel fuel.

Therefore, a number of changes can be introduced to improve operation of the process. However, it should be noted that an improvement in one burden or impact does not necessarily mean improvements in the others. It is therefore necessary to optimise all burdens or impacts of interest simultaneously and then identify the trade-offs between them. This, multiobjective optimisation, approach generates a

number of optimal solutions which show explicitly what can be gained and what lost by choosing each alternative (AZAPAGIC, 1996; AZAPAGIC and CLIFT, 1998, 1999b). The main advantage of this method is that generating optimum solutions does not require *a priori* articulation of preferences, so that the whole set of solutions can be explored. The emphasis is then on the range of choices from a series of solutions, rather than definition of preferences before analysing all the trade-offs among objectives.

Although the choice of the best compromise solution will still imply certain preferences and value judgements, at least the choice will be made from all possible solutions, unlike other methods where the bulk of solutions may be ignored before the analysis. This approach has the further advantage that it avoids the aggregation of environmental impacts into a single environmental impact function in the Valuation phase and the philosophical and methodological objections to this approach (AZAPAGIC, 1996). Furthermore, this approach to process environmental management proves that it is much more useful to analyse the system at the level of the burdens or impacts, as they contain detailed information about the process which would otherwise have been obscured by Valuation. In addition, by being able to trade-off incommensurable objectives, i.e. categorically different environmental burdens or impacts, this approach avoids the well known problems encountered in cost-benefit analysis and other approaches using some form of Valuation (see e.g. PEARCE, 1983), which attempt to reduce individual preferences to a market value or try to express quality of the environment in financial terms.

The multiobjective optimisation approach to process management in the LCA context can also be useful in identifying optimal ways to comply with legislation. In cases where legislation is not prescriptive but allows the use of the Best

Available Techniques (BAT) as, for instance, in the EC Integrated Pollution Prevention and Control (IPPC) directive (EC, 1997), this kind of approach can help identify alternative raw materials, energy sources, technologies and suppliers that will have a minimum impact on the environment. Furthermore, not only does this enable the process industries to comply with legislation, it also provides them with a vehicle for taking a proactive approach that extends beyond compliance through the analysis of "what if" scenarios. In this way, an integrated approach to process management may provide both commercial and market advantages, as well as helping to identify more sustainable industrial practices for the future.

5 Conclusions

Life Cycle Assessment is an effective tool for process environmental management. The Inventory and Impact phases enable identification of "hot spots" or operations in the system which cause the greatest impacts. These activities are then targeted as priorities for improvement. System optimisation can be used as a tool in the Improvement Assessment phase to identify optimal options for improving process performance.

The case study of a process producing five different boron products illustrates this approach. The "hot spots" in this process, targeted for improvements, include Mining, Primary process, Steam production, Boric acid plant, and Packing and shipping. A system optimisation approach can be used to identify the optimal improvement options. Single-objective optimisation on each burden and impact in turn shows that it is possible to reduce burdens by on average 11% and impacts by 20%, while maintaining the product output. However, for an overall improvement of the performance, multiobjective optimisation must be used. In addition to avoiding Valuation, adopting this approach could enable the process industries in general to take a proactive approach to environmental system management and identify more sustainable options for the future.

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Appendix

Flow diagrams of product systems in the Background system

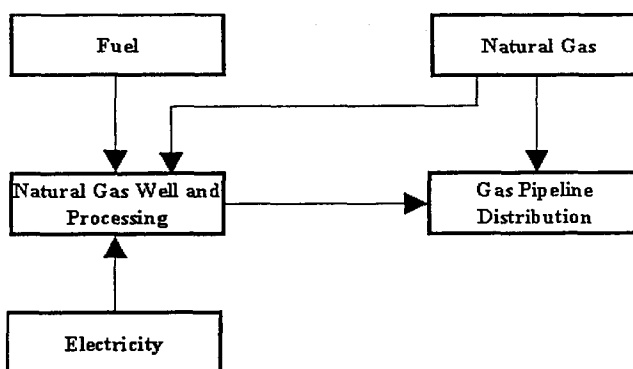


Fig. A.1: Flow diagram for natural gas (use in the Foreground: Cogeneration plant, Primary process, AB and ABA plants, Mine)

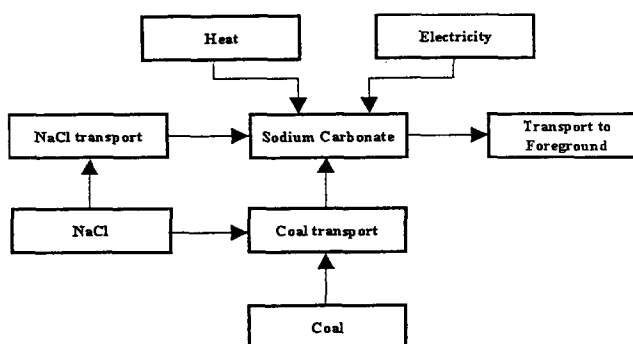


Fig. A.2: Flow diagram for soda ash (Solvay process) (use in the Foreground: Mine)

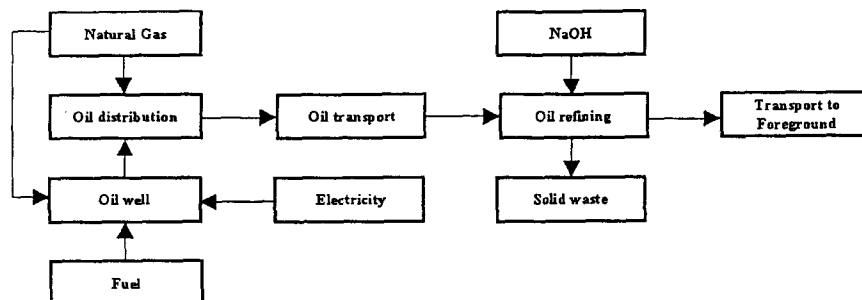


Fig. A.3: Flow diagram for diesel fuel
(use in the Foreground: Mine)

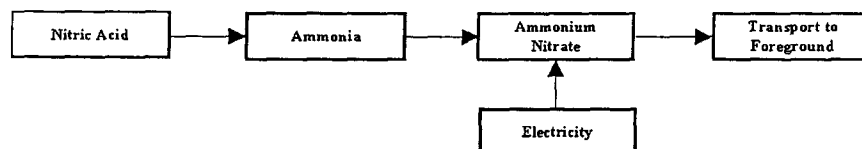


Fig. A.4: Flow diagram for explosive (ammonium nitrate)
(use in the Foreground: Mine)

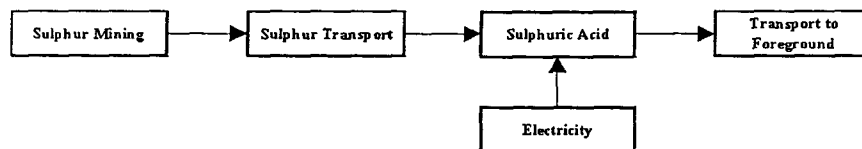


Fig. A.5: Flow diagram for sulphuric acid
(use in the Foreground: BA Plant)

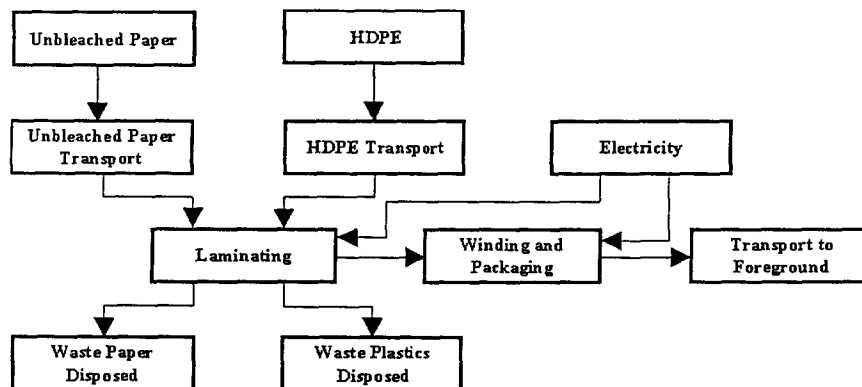


Fig. A.6: Flow diagram for paper bag packaging
(use in the Foreground: Packing & Shipping)

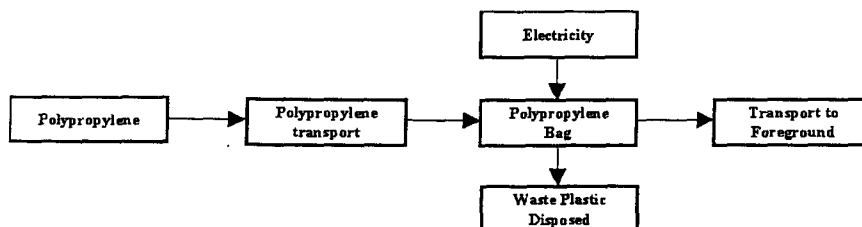


Fig. A.7: Flow diagram for polypropylene bag packaging
(use in the Foreground: Packing & Shipping)